INVESTIGATION OF THE EFFECTS OF FINE-SCALE ATMOSPHERIC INHOMOGENEITIES ON INFRASOUND PROPAGATION

Robert G. Gibson[1], David E. Norris[1], and Douglas P. Drob[2]

BBN Technologies[1] and Naval Research Laboratory[2]

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ABSTRACT

Recent infrasound observations and related research work in long-range sound propagation indicate that fine-scale atmospheric inhomogeneities contribute to refraction, scattering, and related phenomena that can result in anomalous infrasonic arrivals. Gravity waves, in particular, have been shown through physics-based modeling to be responsible for infrasonic arrivals, at regional ranges, that are not predicted by standard modeling techniques. Atmospheric turbulence can also cause scattering of infrasound that produces arrivals in shadow zones at local ranges from ground based sources.

We seek to improve understanding of the effects of gravity waves and other fine-scale atmospheric inhomogeneities, such as Kelvin-Helmholtz turbulent instability, on infrasound propagation. The approach is to build on recent advances in specifying the lower and middle atmosphere, state-of-the-art infrasound propagation calculation techniques, and existing stochastic models of gravity waves and turbulence. Atmospheric specification techniques are being developed that incorporate realistic models of gravity waves that are self-consistent with the background flow field and that include effects of altitude, latitude, longitude, and time-evolution over relevant scales.

The research effort includes systematic evaluation of the relevant atmospheric phenomena, improved atmospheric specification, advancement of the state-of-the art of modeling the interactions between fine-scale atmospheric inhomogeneities and infrasound, and model validation studies using ground truth datasets, focusing on local and regional ranges. Anticipated results of the work include new modeling tools to improve capability to predict infrasound arrivals and features relevant to phase classification at local and regional ranges.

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OBJECTIVES

The objective of this research effort is to improve understanding of the effects of gravity waves and other fine-scale atmospheric inhomogeneities on infrasound propagation. The improved understanding of the relevant atmospheric and infrasonic physics will result in enhanced capabilities for modeling infrasound features and waveforms.

It is evident that existing propagation modeling, coupled with state-of-the-art atmospheric characterizations, fails to adequately predict infrasonic arrivals in all circumstances. In particular, there have been numerous events for which infrasound arrivals are observed by sensors in regions that are predicted by standard modeling techniques to be in shadow zones. (e.g., Bhattacharyya et al., 2003; Kulichkov, 2004; Norris et al., 2006; Mutschlecner and Whitaker, 2006; Norris, 2006) This issue is relevant over both local and regional ranges.

Recent scientific work in gravity waves, atmospheric turbulence, long-range acoustic propagation, and infrasound has indicated that fine-scale atmospheric inhomogeneities contribute to refraction, scattering and related effects that result in unexpected infrasonic arrivals. Investigators use terms such as “leaky ducts” to explain infrasound propagation effects that are not fully understood scientifically. We endeavor to address this issue through systematic evaluation of the relevant atmospheric phenomena, advancement of the state of the art of modeling the interactions between fine-scale atmospheric inhomogeneities and infrasound, improved atmospheric specification, and model validation.

Specifically, the objectives are as follows:

- Review recent scientific progress in the understanding of gravity waves, their temporal and spatial variability, and their statistics, in order to develop an improved model of the characteristics of gravity waves that are relevant to infrasound propagation.
- Develop atmospheric specification techniques that incorporate realistic models of gravity waves in a manner that maintains self-consistency with the background flow field and that includes effects of latitude, longitude, and time-evolution over relevant scales.
- Exercise the improved gravity wave models with infrasound propagation models. Examine variability of infrasound predictions over a statistical ensemble of gravity wave realizations. Perform sensitivity studies to establish the effects of key atmospheric model variables on infrasound prediction.
- Improve understanding of additional classes of fine-scale atmospheric inhomogeneity, such as Kelvin-Helmholtz turbulence instability, and their effects in order to improve modeling of infrasound propagation at local ranges.
- Perform model validation studies using ground truth datasets, focusing on local and regional ranges.

In order to advance the state of the art for high-fidelity infrasound predictions in the presence of fine-scale inhomogeneities, it is necessary to develop propagation models and atmospheric characterizations that capture more of the fundamental physics that affect infrasound. This research effort primarily addresses improved atmospheric specifications that incorporate additional physical effects and the coupling of these specifications with physics-based propagation models. The resulting atmospheric characterizations will include an improved spectral gravity wave model assimilated with the background winds and temperature.

Propagation modeling will address the variability in the path of energy in the atmosphere by exercising models through multiple realizations of the environment. The fine-scale structure examined will include both atmospheric gravity waves and turbulence-driven inhomogeneities such as Kelvin-Helmholtz instability. Because atmospheric fine-scale structure is inherently turbulent, there is no deterministic model for the scalar and vector atmospheric fields associated with the turbulence; instead turbulence can be characterized by modeling the energy distribution across spatial scales using spectral formulations. These spectral models can then be used to generate representative realizations of variable fields. They also can be used directly in formulations that quantify their effect on scattering and related propagation phenomena.

The effort is anticipated to increase understanding of the regional and local propagation of infrasound through the dynamic atmosphere and also to improve the capability to predict infrasound arrivals and features relevant to phase classification. Research results are anticipated to include spectral-based atmospheric variability specifications; numerical modeling subroutines that enable improved propagation modeling via incorporation of effects of gravity waves and other fine-scale atmospheric structure phenomena; and a summary of model/data comparison results.

RESEARCH ACCOMPLISHED

Atmospheric Specification

The atmospheric structure responsible for the propagation of infrasound can change rapidly. Fine-scale atmospheric structures can be responsible for infrasonic refraction, advection, and scattering. Through recent research efforts, BBN Technologies (BBN) and the Naval Research Laboratory (NRL) have contributed to the current state of the art of infrasound modeling by developing and integrating propagation models and high-fidelity atmospheric specifications.

Global climatological models have largely been replaced in current infrasound modeling practice by the NRL Ground to Space (G2S) model of Drob et al. (2003, 2004), which was developed to provide background atmospheric information for the Nuclear Explosion Monitoring Research and Development program. The G2S data processing system combines operational numerical weather prediction (NWP) specifications with the upper atmospheric empirical models, NRLMSISE-00 and HWM-93 (Picone et al., 2002; Hedin et al., 1996). The near-real-time system incorporates 1ºx1º and 1ºx1.25º resolution global NWP input fields to the nearest 6-hour interval in the lower atmosphere.

Through a collaborative project involving NRL and BBN, the G2S system has recently been upgraded to include operational mesoscale (regional) NWP analysis products (with ~20 km horizontal resolution) in order to improve the temporal, horizontal, and vertical resolution in the 0 to 35 km region (Gibson et al., 2006). Regional atmospheric specifications from national and DoD weather centers have a high spatiotemporal resolution and accuracy compared to comprehensive global specifications. This is achieved by focusing additional efforts on the meteorological observations and atmospheric physics specific to a given geographic region. G2S-Mesoscale specifications also provide extra information at the surface by utilizing a terrain-following coordinate system, including high-resolution topography, and additional atmospheric boundary layer effects. In the current implementation of the G2S-Mesoscale model, the specification has 96 vertical levels, with the majority of levels in the first 25 km. These specifications are then interpolated to a regularly spaced latitude and longitude grid at 0.125° intervals.

However, these specifications are unable to resolve all fine-scale stochastic phenomena, e.g., atmospheric irregularities smaller than the model resolution, fine-scale structures above 35 km, and gravity wave fluctuations that cannot be deterministically measured or internally generated by the model. Fine-scale atmospheric structure not characterized by near-real-time atmospheric models such as G2S has been identified as a likely source of refraction and scattering effects that may play a significant role in infrasound propagation. In particular, gravity waves are of interest because their spatial scales are of the same order as infrasonic wavelengths.

Propagation Modeling

The atmospheric specifications described above and a suite of infrasound propagation models (including 3-D ray-tracing, parabolic equation (PE), time-domain parabolic equation (TDPE), and normal modes) are currently integrated into the tool kit InfraMAP (Gibson and Norris, 2002; Norris and Gibson, 2004). InfraMAP (*Infrasonic Modeling of Atmospheric Propagation*) has been developed by BBN for use in the study of infrasound propagation and monitoring. InfraMAP can be applied to predict attenuation, travel times, bearings, amplitudes, and waveforms for infrasonic events. It also provides the ability to define a local network of stations and compute event localizations and associated error ellipses from station measurements and propagation predictions. The most recent version of InfraMAP includes TDPE waveform prediction capabilities based on either the Pierce blast wave or any user-defined waveform (Norris et al., 2005). The propagation models in InfraMAP have been used for a wide range of infrasound event analyses and validation studies.

Acoustic propagation through various types of inhomogeneous media have been studied (e.g., Ostashev, 1997), but fundamental issues have not been thoroughly investigated or validated for infrasound. Propagation through turbulence in the ocean and atmosphere has been treated using phase screen methods, which are computationally efficient but do not incorporate all of the relevant physics. The significance of the background internal wave spectrum in ocean acoustics has been studied and is well understood (e.g., Colosi, 2006). Much progress has been made in understanding propagation through locally homogeneous and isotropic turbulence in the atmosphere, but many problems still remain related to effects of turbulence intermittency and mesoscale anisotropic coherent structures (Kallistratova, 2002). Understanding infrasound propagation through atmospheric internal gravity waves is an emerging scientific topic, as discussed below.

Modeling Variability due to Gravity Waves

Atmospheric properties vary in both space and time. Coherent spatial variability is observed at length scales from meters to thousands of kilometers, and temporal variability occurs over diurnal and seasonal time scales. The variability in wind and temperature makes modeling infrasound propagation difficult. Since the environment is dynamic and cannot be measured over the entire region through which the infrasonic signals propagate, stochastic modeling methods are necessary to account fully for the environment's influence on propagation.

The dominant source of variability affecting infrasonic propagation (beyond the synoptic-scale meteorology) is believed to be gravity waves, because their spatial scales are of the same order as infrasonic wavelengths. Gravity waves result from oscillations of air parcels displaced by buoyancy and restored by gravity. The oscillations have time scales ranging from minutes to tens of hours. Vertical length scales of gravity waves are in the range of 0.1 to 15 km, and horizontal scales can span from 10 to 1000 km. The multiscale nature of gravity waves presents a challenge to quantification of their properties. Owing to the important influences of gravity waves on the atmosphere’s general circulation, vertical structure, and spatiotemporal variability, gravity wave dynamics is a significant atmospheric science research topic area. Recent research progress includes a better understanding of gravity wave source characteristics, evolution with altitude due to changes in wind conditions, and atmospheric stability (e.g., Fritts and Alexander, 2003). The development of high-fidelity physically-based gravity wave parameterizations is an active research area.

InfraMAP includes a baseline environmental variability model for predicting infrasound deviations due to atmospheric effects that are not resolved by the existing atmospheric specifications. The most basic variability model in InfraMAP uses a power-law wind perturbation spectrum, and it provides realizations of wind perturbation profiles. This spectrum is applicable primarily for small-scale turbulence, even though atmospheric turbulence covers a wide spectrum of spatial scales. A significant body of research has been carried out to define the spectral character of gravity waves. The spectral model of Gardner (1995, 1993) was selected for integration into InfraMAP’s environmental variability module. This model is based on scale-independent diffusive filtering theory. A source spectrum is defined near the ground. As the spectrum is propagated up in height, attenuation is modeled by introduction of diffusive damping. The key spectral properties are increase in energy with height; shift towards larger length scales with height; and attenuation of smaller length scales with height.

Wind perturbations due to gravity waves are modeled in the spectral domain (Norris and Gibson, 2002), and both height and range-dependent gravity wave dependencies are modeled. The spectral model is used to generate multiple realizations of the perturbed environment, which in turn are used to quantify the statistical variability of the propagation. For ray-tracing, a Monte Carlo simulation may be executed where multiple rays are traced through the sum of mean and perturbed profiles. This simulation can be used to estimate moments of travel-time and azimuthal deviation. Atmospheric variability models have also been integrated into PE and TDPE models. Model predictions can be made through atmospheric “snapshots” of the inhomogeneities. These predictions capture the effects of the atmospheric variability on waveform metrics, such as amplitude, travel time, duration, and spectral content.

The Gardner spectral model is evaluated at four discrete heights, as shown in Figure 1 (Norris and Gibson, 2002). These heights capture the dominant gravity wave variability from the troposphere up to the lower thermosphere. Gravity waves are not fully developed below the troposphere. In the thermosphere, diffusion increases dramatically and gravity waves are damped out. Predicted standard deviations of wind perturbations are listed in the figure alongside the spectral heights.

Fourier inversion using random phase is applied to the spectra to generate realizations of wind perturbation profiles. A wind perturbation profile is generated for each of the five spectra. A composite profile is then computed by shading each profile spatially with a Gaussian filter and then summing them together, where Gaussian filter half-power points are set to the midpoint between each of the spectral heights. To model range-dependent variability, a dominant horizontal length scale is defined, and Gaussian weighting functions are used to combine the wind perturbation profiles.

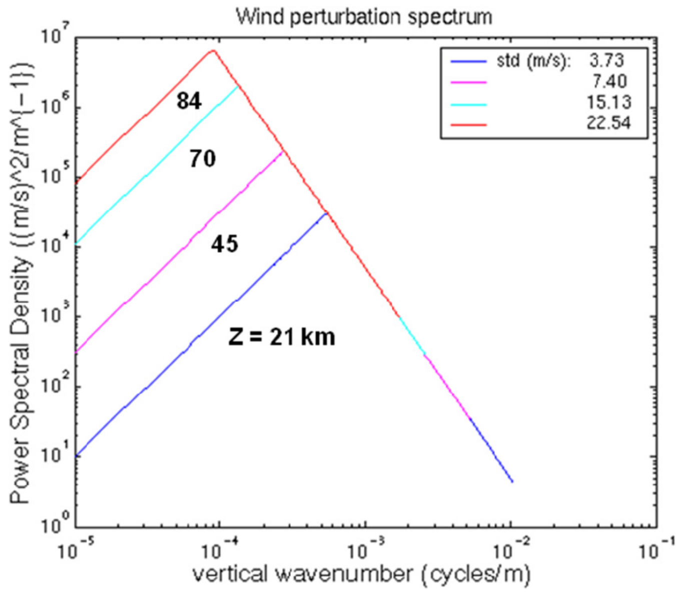

Figure 1. Wind perturbation spectra from Gardner's gravity wave model evaluated at 5 discrete heights.

Using our existing model, propagation variability studies have been conducted for various scenarios and event analyses. One finding has been that new propagation features can be seen with the introduction of range-dependence in the environmental variability models. Use of range-dependence in the gravity wave model more realistically models the horizontal scales associated with gravity wave observations. Modeling studies to date have indicated the presence of transient ducts that can significantly perturb travel times and signal velocities. These ducts form around localized minima in the sound speed, and their extent is determined by the horizontal correlation length of the gravity waves. Models of perturbed rays suggest that energy can get trapped within shallow transient ducts that form between gravity wave layers. One effect of this propagation mode is a reduction in the overall travel time and increase in signal velocity.

Approaches to Improved Gravity Wave Modeling

As reviewed above, existing approaches to modeling infrasound through gravity waves have relied on one-dimensional vertical wavenumber spectral models. This simplified model approach captures the vertical spatial scales in gravity waves as a function of height. We intend to extend this capability by accounting for additional dimensional variability, including horizontal wavenumber, which can be characterized using Gardner's spectral model. Given a spectral model, numerous parameters must be defined in order to apply it. For example, in the Gardner model, the parameters include peak spectral magnitude, dissipation rate, and dominant wavenumber. In work conducted to date, a single representative set of parameters was defined for use in all propagation scenarios. During this research effort, we will consider spatial and temporal dependencies in the parameter selection. For example, the peak energy parameter will be quantified from near-real-time atmospheric data for a given location or formulated based on latitude and Julian day. In addition, there exist more complex 2-D and 3-D spectral models that provide increased fidelity and insight into gravity wave structure (e.g., Ostashev et al., 2005). These models will also be considered for use during the research effort.

The baseline Gardner model does not account for the fact that gravity wave fields can vary dramatically with altitude, latitude, and season (e.g., Eckermann, 1995). This significant variability results from the corresponding changes in the background wind and static stability profiles. Thus there is a need to improve on the existing spectral approach used by Norris and Gibson (2002) to account for more realistic geophysical variability of the gravity wave spectra. Since the work of Gardner (1995, 1993), there have been a number of spectral gravity wave parameterization schemes that have sought to account for these additional effects. Development of these parameterizations is motivated by national efforts to improve general circulation modeling and numerical weather prediction of the lower and middle atmosphere.

The model of Gardner (1995, 1993) will be augmented by one that takes into account the refraction and reflection of a spectrum of gravity waves by arbitrary height-dependent winds and stratification. Models of this type have already been tested for other applications by the Middle Atmosphere Group at NRL. Wind shifting (refraction) of gravity wave spectral densities was parameterized and tested observationally by Eckermann (1995) based on a simple wind shifting model of Fritts and Lu (1993). That technique was extended by Warner and McIntyre (2001) to account more realistically for dissipation and spectral wave action conservation. A reasonable starting point for the current work, then, is the model of Warner and McIntyre (2001), which uses several idealizations that can be successively relaxed as the research results dictate.

The need to self-consistently account for gravity wave effects and variability by using as much observational data as possible is very important to both the understanding and the application of this problem. An over- or under-estimation of the gravity wave amplitudes and fluctuations in the background field will lead directly to an over- or under-estimation of scattered or refracted infrasound. Given extensive observational data, parameterizations of the refractive response of these energy spectra to background wind shear and stability changes can be extensively validated against data, as has been done in previous applications (e.g., Eckermann, 1995; Bacmeister et al., 1996). Extension of these studies to the current application and newer and more extensive observations of gravity wave spectral properties will be used to observationally constrain and validate our new spectral parameterizations and their response to environmental conditions specified by G2S. The result is anticipated to be realistic stochastic mesoscale variability at any given height and geophysical location.

All of the prerequisites for calculating the vertical and horizontal amplitudes of the random gravity wave perturbations (U, V, T, P, ρ) are provided by the available G2S specifications. We intend to develop and test subroutines needed to generate ensembles of random gravity wave perturbation fields that are dynamically self-consistent (to first order) with corresponding G2S atmospheric specifications. We are also undertaking development of subroutines that provide the stochastic gravity wave perturbation fields (u',v', t', p', and ρ') as a function of z, x, y and t given the corresponding G2S background atmospheric fields (u, v, t, P and ρ) over the same spatial domain z, x, y. These routines will account for the important seasonal, latitude, longitude dependence of the various auxiliary model parameters, such as the gravity wave spectrum lower cut off wave number (m^*), which, together with the background atmospheric state, govern the nature and amplitude of the gravity wave spectrum.

This gravity wave fluctuation module, which we envision will ultimately be integrated into the G2S client software library, will provide a representation of the random gravity wave background field and its variability for infrasound propagation modeling, given current scientific understanding and modeling capabilities for gravity waves.

Approaches to Modeling Turbulence Inhomogeneities

There exists other fine-scale structure in the atmosphere, in addition to gravity waves, that has spatial scales on the same order as infrasound and which thus may influence infrasonic propagation. As part of this effort, we intend to explore the modeling of additional regions in the atmosphere where turbulent source mechanisms may affect propagating wavefronts. One source already identified is that generated by Kelvin-Helmholtz instabilities, or shear instabilities.

At altitudes of 10 to 15 km, a layer exists called the jet stream that is characterized by a stable, strong wind flow. The boundary between the jet stream and the more static fluid above it can become unstable. This instability results from the shear stresses between the two layers. The instability manifests itself through the generation of Kelvin-Helmholtz waves (Nappo, 2002). These waves are coherent perturbations of both scalar and vector fields in the boundary region. They start as rolling undulations and then evolve to a wave-like structure that eventually breaks down into vortices or billows. Kelvin-Helmholtz waves are often present within layers of moderate and severe clear air turbulence.

Because Kelvin-Helmholtz waves have very pronounced spatial features, spectral models do not capture the relevant structure that may affect infrasound. Therefore, as part of this effort, we intend to develop models that capture the dominant spatial features within the waves. For example, a wind perturbation model can be developed that provides a realization of the vector wind in the early, middle, and late phases of the evolving Kelvin-Helmholtz wave. This model can then be assimilated into the background atmospheric state, as provided by G2S, and then used in propagation modeling studies.

Approaches to Improved Propagation Modeling

Fundamental understanding is needed of the physics of infrasound propagation through the inhomogeneous atmosphere. Much experimental and theoretical work has been done in the former Soviet Union on the interaction of low-frequency sound and infrasound with turbulence. In particular, many measurements have been conducted and reported, along with theoretical developments, by researchers at the Oboukhov Institute of Atmospheric Physics in Moscow. Some of these results are reviewed by Kulichkov (2004), who has observed “partial reflection (scattering)” of low-frequency acoustic or infrasonic pulses from fine-layered inhomogeneities in the middle atmosphere. These observations include “rapid variations” of infrasonic signals from a series of similar ground-based explosions timed at intervals of 10-30 minutes and observed at local or near-regional ranges. The signal variations, with time scales similar to the periods of internal gravity waves, and intermittent observations of signals in shadow zone regions are attributed to inhomogeneous coherent structure in the atmosphere (Kulichkov, 2004).

Further review of relevant investigations is presented by Kallistratova (2002). Scattering of sound from tropospheric gravity waves is discussed as a mechanism for explaining observed low-frequency signals. Quasi-regular inhomogeneities of temperature field and wind velocity or coherent structures that are “vertical, pancake and undulatory” all affect acoustic and infrasonic waves, and strong anisotropy of “pancake” structures in the stratosphere are particularly important for long-range propagation from explosions. “Horizontally stretched” anisotropic inhomogeneities can exist at both stratospheric and mesospheric heights and can theoretically explain observations by Kulichkov and his colleagues (Kallistratova, 2002). Kallistratova (2002) also emphasizes that it is necessary when considering nonlinear propagation phenomena to also consider the effect of turbulent fluctuations.

There have been a small number of theoretical papers dealing directly with the subject of infrasound in the inhomogeneous atmosphere (e.g., Chunchuzov, 2004; Ostashev et al., 2005, Chunchuzov et al., 2006). These authors point out that this subject involves combining two difficult topic areas: 1) three-dimensional spectra of temperature and wind velocity fluctuations due to gravity waves in a stably stratified atmosphere; and 2) a general theory of sound propagation refracted and scattered by anisotropic turbulence with both temperature and wind velocity fluctuations. While theoretical treatments exist, there has been limited progress toward validated numerical propagation calculation techniques for infrasound in turbulent structure.

Two modeling approaches will be undertaken in this effort with regard to assimilating the fine-scale atmospheric structure for use in propagation predictions: field realizations and random media formulations.

In the first approach, inverse Fourier transforms of the spectral models are taken to generate realizations of the variable fields. Random phases are added to the spectral bins so that each realization is different while as the same time maintaining the correct spatial scales and energetics. The variable fields generated are perturbation fields that reflect the temperature and wind deviations associated with the turbulence. They must be assimilated with the mean background fields to generate an overall solution of the atmospheric state. An example realization of wind fields, using our baseline technique and spectra derived from Gardner (1995, 1993), is shown in Figure 2 (Norris et al., 2006). The gravity waves are seen as thin layers of coherent wind anomalies. The total atmospheric wind realization is seen to be the sum of the mean G2S specification and fine-scale gravity wave structure.

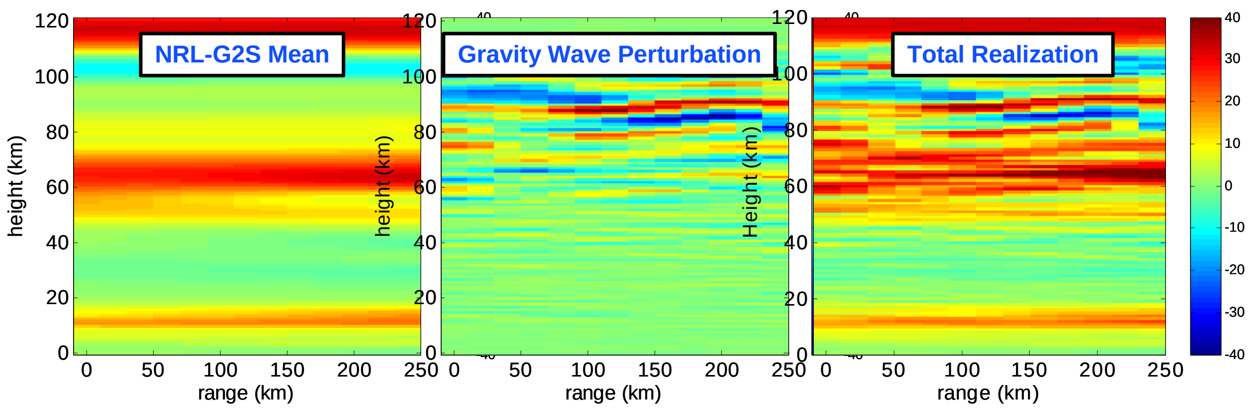

Figure 2. Atmospheric specification showing the G2S mean wind fields (left panel), wind perturbations from gravity waves (middle panel), and resulting total realization (right panel).

In this realization, the perturbed and mean fields are simply added. However, this approach ignores the interdependency between the background atmospheric state and locations of strong turbulent activity. We intend to improve upon this technique by accounting for the self-consistency required to combine the mean and perturbed fields. The self-consistency will be addressed by coupling the gravity wave model with the output of the background G2S model, as discussed in the previous section.

Improvements to propagation modeling techniques will be coupled with improvements to the gravity wave characterizations. The gravity wave model for infrasound can be improved significantly by including the geospatial and temporal dependence on the amplitude scale factor. Other issues to be examined include mean flow bias, maximum flow limits, anisotropy, horizontal correlation length, and zonal vs. meridianal flow dependence. Ultimately, by better defining the scales and amplitudes of the relevant environmental perturbations, better estimates of the stochastic properties of infrasound propagation are expected to be obtained.

The second approach to integrating the atmospheric models relies on well-developed theory of propagation through random media (Ostashev, 1997). By applying this theory, direct predictions of propagation variables can be made. The formulations require spectral models of the turbulence as input. We will use the spectral models as described above to directly predict the effects of fine-scale structure on the propagation. Variables that will be predicted include scattering cross section, scattering angle, coherence length, and mean pressure levels (Ostashev et al., 2005).

CONCLUSIONS AND RECOMMENDATIONS

Model validation studies of infrasound observations using ground truth data have been conducted to build confidence in atmospheric specification procedures and calculation techniques and to identify areas where further refinements are required to achieve improved infrasound predictions. Substantial evidence for the importance of variability due to fine-scale inhomogeneity has been indicated by TDPE waveform predictions for several events observed at regional ranges (e.g., Norris et al., 2006; Norris, 2006). In several instances, conventional propagation modeling has failed to predict observed arrivals due to the lack of a stratospheric duct in the baseline atmospheric characterization; these observations exist in so-called "shadow zones." However, modeled infrasound arrivals that considered stratospheric energy refracted or scattered from gravity waves agreed well in waveform shape, extent and arrival time with observations.

These results indicate the considerable benefit to regional monitoring that is to be gained by understanding gravity wave effects on infrasound. While implementation of our existing baseline gravity wave model enables prediction of certain infrasound features, there is significant additional understanding of the fundamental physics yet to be gained and additional model fidelity that is needed. It is anticipated that the dominant effects of gravity waves on infrasound are observed over regional paths. Local paths are also of significant interest as they are affected by turbulent instabilities and may represent the only observable energy for small events.

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